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भाग 4 ताप सहायता रूपरेखा आकलन के लिए अनुदेश

Indian Standard

GUIDE FOR DETERMINATION OF THERMAL ENDURANCE PROPERTIES OF ELECTRICAL INSULATING MATERIALS

PART 4 INSTRUCTIONS FOR CALCULATING THE THERMAL ENDURANCE PROFILE

UDC 621·315·61 : 620·199

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NEW DELHI 110002

March 1994 **Price Group 8**

Solid Electrical Insulating Material Sectional Committee, ETD 02

FOREWORD

This Indian Standard (Part 4) was adopted by the Bureau of Indian Standards, after the draft finalized by the Solid Electrical Insulating Material Sectional Committee had been approved by the Electrotechnical Division Council.

This standard is part of the following series of standards:

Part 1 General guidelines for ageing procedures and evaluation of test results
Part 2 List of materials and available tests
Part 3 Statistical methods
Part 4 Instructions for calculating the thermal endurance profile

In the formulation of this standard, assistance has been derived from IEC 216-3 'Guide for the determination of thermal endurance properties of electrical insulating materials : Part 4 Instructions for calculating the thermal endurance profile' issued by the International Electrotechnical Commission.

Indian Standard

GUIDE FOR DETERMINATION OF THERMAL ENDURANCE PROPERTIES OF ELECTRICAL INSULATING MATERIALS

PART 4 INSTRUCTIONS FOR CALCULATING THE THERMAL ENDURANCE PROFILE

1 SCOPE

This part gives detailed instructions for calculating the thermal endurance profile of electrical insulating materials from thermal endurance test results, according to IS 8504 (Part 3) : 1993.

2 REFERENCES

The following Indian Standards are necessary adjuncts to this standard:

IS No.	*Title*
8504	Guide for determination of thermal endurance properties of electrical insulating materials:
(Part 1) : 1993	Temperature indices and thermal endurance profiles
(Part 2) : 1983	List of materials and available tests
(Part 3) : 1993	Statistical methods

3 OBJECT

Statistical methods for determination of the thermal endurance profile of electrical insulating materials are described in IS 8504 (Part 3): 1993.

In this part, detailed instructions are given for making the calculations according to these methods. The instructions are illustrated by means of numerical examples showing the calculations step by step.

During the calculation, the statistical test variables are compared with the values tabulated in Annex A.

The examples comprise three cases:

Example 1 Continuous measurements

Example 2 Cyclic application of proof test

Example 3 Destructive measurements

In examples 1 and 2, the calculations are shown as carried out using a simple desk calculator. In example 3, the use of an electronic desk calculator with built-in statistical programmes is assumed. The calculations, therefore, present themselves in a somewhat different and much shorter form, but could easily be transformed to the format of examples 1 and 2 (and *vice versa*).

4 ASSUMPTIONS

The assumptions underlying the following siatistical procedures are:

a) The observed values of time to failure are *stochastically independent*. The specimens used for the ageing test constitute a random sample from the population investigated, and were treated uniformly.

b) The logarithm of time to failure is *normally distributed* with the *same variance* at all temperatures.

c) The logarithm of time to failure depends linearly on the reciprocal thermodynamic ageing temperature (Arrhenius' equation) at least over a range including all test points and extrapolated points.

d) The exposure temperature has negligible error, and is the same for all specimens exposed together.

5 TEST PROCEDURES AND DATA

In order to determine the thermal endurance profile (TEP) of an electrical insulating material according to a prescribed end-point criterion, a specified number of specimens are exposed to each of a series of selected temperatures, and the times to failure determined.

The temperatures are selected in accordance with IS 8504 (Part 1) : 1993, and a group of specimens is aged at each temperature either by cyclic or by continuous ageing. The determination of the times to failure, that is time when a specified property passes a given end-point criterion, depends on the test procedure.

5.1 Repeated Tests

Each specimen is tested repeatedly during ageing, either by continuous measurement of the specified property, or at fixed times by measurement or application of a specified proof stress. If the property is measured continuously, the time to failure for each specimen is obtained directly from the recorded values as the time when the property passes the end-point criterion.

This applies to all cases where a property is monitored continuously or by frequent scanning during ageing by non-destructive measurements. If the property is measured at fixed times during ageing, the property (or a predetermined function of the property) is plotted versus time (or a function of the time), and the individual times to failure determined from the graph as the time when the property of the individual specimens passes the end-point criterion.

This procedure applies to continuous and cyclic ageing tests, where a property is measured at infrequent intervals (for example at the end of ageing cycles) by non-destructive measurements. In some cases it may be sufficient to consider the end-point criterion as a proof value, and use the procedure below.

If a proof stress is applied at fixed times during ageing, the time to failure for each specimen is determined as the mean of the time when the specimen first failed to pass the proof test and the immediately preceding measuring time, that is, the time to failure is taken as the midpoint of the last cycle to which the specimen is exposed.

This procedure applies to cyclic tests where all the specimens are tested by proof stress at the end of each cycle, and then exposed to a new cycle, as long as they pass the proof test.

5.2 Single Test on Each Specimen

In each case the property values are plotted versus time in a graph for each temperature, and a curve making the best fit of the points is drawn. At the four measuring times nearest to the crossing point of the best fitting curve and the line representing the end-point criterion, curves are drawn parallel to the best fitting curve through the individual measured points. The points where these curves cross the end-point line are taken as the individual times to failure.

This procedure is used in cases where the property is determined by destructive measurements, and cases of continuous ageing where at fixed times only a specified number of specimens are removed from the oven and discarded after measurement.

6 STATISTICAL CALCULATIONS AND DECISIONS

For each value of the k different temperatures θ_i °C (i = 1,2,.. k), calculate the reciprocal value of the thermodynamic temperature

$$x_i = \frac{1}{\theta_i + 273}$$

and the common (Briggsian) logarithm (that is the logarithm to the base of 10) of the times to failure

$$y_{ij} = \lg t_{ij}.$$

Here t_{ij} is the time to failure of specimen No. j at temperature θ_i °C ($j = 1, 2, \ldots n_i$) where n_i is the number of specimens exposed at θ_i °C; The total number of specimens equals $N = \Sigma n_i$.

6.1 Testing the Equality of the Variances of y_{ij}

Calculate the variances s_{ii}^2 at the different values of x_i

$$s_{ii}^2 = \frac{n_i \, \Sigma y_{ij}^2 - (\Sigma y_{ij})^2}{n_i \, f_i} \qquad f_i = n_i - 1$$

and the pooled variance

$$s_i^2 = \frac{\Sigma f_i \, s_{ii}^2}{\Sigma f_i} \quad f_i = \Sigma f_i = N - k$$

These variances are compared by Bartlett's test. One calculates

$$c = 1 + \frac{\left(\Sigma \dfrac{1}{f_i} \right) - \dfrac{1}{f_i}}{3 (k - 1)},$$

and the test variable

$$\chi^2 = 2{\cdot}3 \, . \frac{f_i \cdot \lg s_i^2 - \Sigma (f_i \cdot \lg s_{ii}^2)}{c} \, .$$

The test variable χ^2 is compared with tabulated value X^2 (0·95, k − 1) from Annex A.

If $\chi^2 > \chi^2$ (0·95, k − 1), the value of χ^2 shall be reported in connection with the thermal endurance profile.

6.2 Regression Coefficients

Calculate the coefficients of the regression equation

$$y = a + bx$$

from

$$\bar{x} = \frac{\Sigma n_i \, x_i}{N}$$

$$\bar{y} = \frac{\Sigma y_{ij}}{n_i}$$

$$\bar{y} = \frac{\Sigma n_i \, \bar{y}_i}{N}$$

as

$$b = \frac{N\Sigma (x_i \, \Sigma y_{ij}) - (\Sigma n_i \, x_i) (\Sigma\Sigma y_{ij})}{N\Sigma n_i \, x_i^2 - (\Sigma n_i \, x_i)^2}$$

and

$$a = \bar{y} - b\bar{x}.$$

Draw the regression line on a thermal endurance graph (*see* Fig. 1).

6.3 Test for Linearity

Calculate

$$s_2^2 = \frac{(\Sigma n_i \bar{y}_i^2 - N\bar{y}^2) - b\,(\Sigma n_i x_i \bar{y}_i - N\bar{x}\bar{y})}{f_2}$$

where

$$f_2 = k - 2.$$

and the ratio s_2^2 and s_1^2 from **6.1**.

$$F = \frac{s_2^2}{s_1^2}$$

The test variable F is compared with the tabulated value $F\,(0{\cdot}95, f_n, f_d)$ from Annex A with $f_n = f_2$ and $f_d = f_1$.

If $F > F\,(0{\cdot}95, f_n, f_d)$, the value of F shall be reported in connection with the thermal endurance profile.

A pooled estimate of the variance is calculated as

$$s^2 = \frac{f_1 s_1^2 + f_2 s_2^2}{f}$$

where

$$f = N - 2$$

6.4 Confidence Limit on y

For selected values of X calculate

$$Y = a + bX.$$

and

$$s_y^2 = s^2 \left[\frac{1}{N} + \frac{(X - \bar{x})^2 N}{N \Sigma n_i x_i^2 - (\Sigma n_i x_i)^2} \right].$$

Determine $t = t\,(0{\cdot}95, f)$ from Annex A and calculate the lower unilateral confidence limit on y as

$$Y_c = Y - t\,s_y.$$

where s_y is the square root of the variance s_y^2.

The connected values of X and Y_c are plotted on the thermal endurance graph (*see* **6.2**) and a curve drawn through the points (X, Y_c) on the graph, giving the lower unilateral 95% confidence limit on the true value of y at a given value of x.

6.5 The Coefficient of Variation

From the regression equation one calculates the value X_5 corresponding to $Y_5 = 3{\cdot}7$ (time to failure 5 000 h)

$$X_5 = \frac{Y_5 - a}{b}$$

and the corresponding variance on Y_5

$$s_y^2 = s^2 \left[\frac{1}{N} + \frac{(X_5 - \bar{x})^2 N}{N \Sigma n_i x_i^2 - (\Sigma n_i x_i)^2} \right].$$

If the coefficient of variation

$$CV = \frac{s_y}{3{\cdot}7}$$

is greater than 0·015, the calculations are stopped and only the thermal endurance graph reported.

6.6 Temperature Corresponding to 20 kh and 5 kh to Failure

Calculate

$$X_{20} = \frac{4{\cdot}3 - a}{b}$$

and

$$\theta_{20} = \frac{1}{X_{20}} - 273$$

$$\theta_5 = \frac{1}{X_5} - 273 \text{ (from } \textbf{6.5} \text{)}$$

6.7 Confidence Limit on θ_5

Calculate

$$b_r = b - \frac{t^2 s^2}{b\,\Sigma n_i (x_i - \bar{x})^2}$$

$$s_r^2 = s^2 \left[\frac{b_r}{Nb} + \frac{(X_5 - \bar{x})^2 N}{N \Sigma n_i x_i^2 - (\Sigma n_i x_i)^2} \right]$$

and

$$X_c = \bar{x} + \frac{Y_5 - \bar{y}}{b_r} + \frac{t\,s_r}{b_r}$$

where $t = t\,(0{\cdot}95, f)$ as in **6.4**.

$$\theta_c = \frac{1}{X_c} - 273$$

6.8 Thermal Endurance Profile

The TEP is reported as

$$\theta_{20}/\theta_5\ (\theta_c).$$

7 EXAMPLES

In the following, the calculations are illustrated by means of numerical examples as carried out step by step using a simple desk calculator and possibly a slide rule and a table of logarithms. For convenience the following abbreviations have been used:

S = sum P = product V = variance
D = difference M = mean R = reciprocal
Q = square

so that, for example *SQD* means the sum of the squares of the differences. Indices are placed in parentheses. The use of the symbols will appear from the tables.

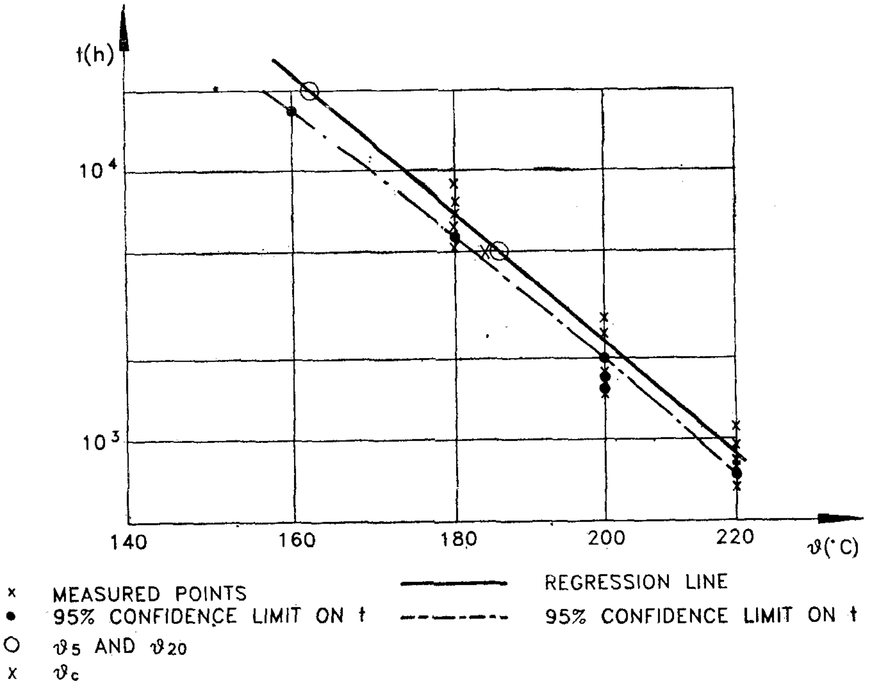

FIG. 1 THERMAL ENDURANCE GRAPH

7.1 Example 1 : Continuous Measurements

A material is tested by continuous measurements of a property, for instance insulation resistance. The time to failure is determined for each specimen as the time when the insulation resistance falls below a specified value (the end-point criterion).

The expected temperature range corresponding to an extrapolated time to failure of 20 000 h is 160°C to 169°C. Three exposure temperatures θ_i°C are selected from Table 1, namely 180°C, 200°C and 220°C, that is $k = 3$ ($i = 1, 2, 3$).

A total of at least $N = 15$ specimens are prepared, and five specimens selected at random are exposed at each temperature, $n_i = 5$ ($j = 1, 2, 3, 4, 5$).

The times to failure, t_{ij} hours obtained are given in Table 2.

Table 2 also shows the calculation of the reciprocal thermodynamic temperature x_i, and the values of $y_{ij} = \lg t_{ij}$. For convenience the values of x have been multiplied by 1 000.

Table 3 shows the calculation of the thermal endurance profile.

7.1.1 The variances s^2_{1i} are calculated as Item (14), V (1, i), with f(i) = 4 degrees of freedom, and the pooled variance s_1^2 as Item (26), V (1) with f(1) = 12 degrees of freedom. The test variable $\chi^2 = 0{\cdot}17$, Item (34), is compared with χ^2 (0·95, 2) = 6·0, Item (35). Since $\chi^2 < \chi^2$ (0·95, 2), the value of χ^2 is not significant on the 5% level.

7.1.2 The regression coefficients $a = -7{\cdot}604$, Item (53), and $b = 5{\cdot}174$, Item (51) are calculated. The regression line

$$y = -7{\cdot}604 + 5{\cdot}174\,x$$

is drawn in a thermal endurance graph (Fig. 1).

7.1.3 The test variable $F = 0{\cdot}7$, Item (63), is compared with F (0·95, 1, 12) = 4·8, Item (64). Since $F < F$ (0·95, 1, 12) the value of F is not significant on the 5% level.

7.1.4 The temperatures 220°C, 200°C, 180°C and 160°C, Item (70), are chosen. The 95% confidence limits t_c Item (83), on the corresponding values of t, Item (84), with Student's t, t (0·95, 13) = 1·77, Item (69), are calculated and plotted on the thermal endurance graph.

7.1.5 The coefficient of variation $CV = 0{\cdot}009$, Item (97), is calculated. Since $CV < 0{\cdot}015$, the calculations are continued.

7.1.6 The vaules $\theta_5 = 185$ and $\theta_{20} = 162$ are calculated as Item (90).

7.1.7 The 95% confidence limit $\theta_c = 182$ on θ_5 calculated as Item (113).

7.1.8 The thermal endurance profile is

TEP = 162/185 (182).

7.2 Example 2 : Cyclic Application of Proof Test

A material is tested by a proof test, for instance application of a specified voltage for one minute in accordance with Table 2 of IS 8504 (Part 2) : 1983 (Test 1.1).

The expected temperature range corresponding to an extrapolated time to failure of 20 000 h is 140°C to 149°C. Three exposure temperatures θ°C and three cycle times t_p hours are selected from Table 1 as shown in Table 4.

Table 1 Suggested Exposure Temperatures and Cycle Durations

(*Clauses* 7.1 *and* 7.3)

	Range to Which the Temperature Corresponding to an Extrapolated 20 000 h Time to Failure is Assumed to Belong, °C														Time per Cycle (Days)
	100	110	120	130	140	150	160	170	180	190	200	210	220	230	
	109	119	129	139	149	159	169	179	189	199	209	219	229	239	
Exposure Temperature °C	170	180	190	200	210	220	230	240	250	260	270	280	290	300	1
	160	170	180	190	200	210	220	230	240	250	260	270	280	290	2
	150	160	170	180	190	200	210	220	230	240	250	260	270	280	4
	140	150	160	170	180	190	200	210	220	230	240	250	260	270	7
	130	140	150	160	170	180	190	200	210	220	230	240	250	260	14
	120	130	140	150	160	170	180	190	200	210	220	230	240	250	28
	110	120	130	140	150	160	170	180	190	200	210	220	230	240	49

NOTE — Exposure temperatures above and below those given are to be selected by experimentation.

Table 2 Test Data and Calculation of the Variables x and y

(*Clause* 7.1)

t = time to failure in hours, y = lg t.

	i	1		2		3	
Number of specimens	n	5		5		5	
Exposure temperature	θ	220		200		180	
Thermodynamic temperature (273 + θ)	Θ	493		473		453	
1 000/Θ	x	2·028		2·114		2·208	
Specimen number	j	t	y	t	y	t	y
	1	1 100	3·04	2 400	3·38	7 410	3·87
	2	740	2·87	1 820	3·26	6 610	3·82
	3	720	2·86	1 660	3·22	6 170	3·79
	4	620	2·79	1 740	3·24	5 500	3·74
	5	910	2·96	2 700	3·43	8 910	3·95

Table 3 Calculation of *TEP*

(*Clauses* 7.1 and 7.2)

		i	1	2	3
(1)	$n(i)$	from Table 1	5	5	5
(2)	$x(i)$	from Table 1	2·028	2·114	2·208
(3)	$Qx(i)$	(2) squared	4·112 784	4.468 996	4·875 264
(4)	$y(i, j)$	from Table 1	3·04 2·87 2·86 2·79 2·96	3·38 3·26 3·22 3·24 3·43	3·87 3·82 3·79 3·74 3·95
(5)	$Qy(i, j)$	(4) squared	9·241 6 8·236 9 8·179 6 7·784 1 8 761 6	11·424 4 10·627 6 10·368 4 10·497 6 11·764 9	14·976 9 14·592 4 14·364 1 13·987 6 15·602 5
(6)	$Sy(i)$	(4) summed	14·52	16·53	19·17
(7)	$SQy(i)$	(5) summed	42·203 8	54·682 9	73·523 5
(8)	$n(i) . SQy(i)$	(1) · (7)	211·019 0	273·414 5	367·617 5
(9)	$QSy(i)$	(6) squared	210·830 4	273·240 9	367·488 9
(10)	$n(i) . SQDy(i)$	(8) − (9)	0·188 6	0·173 6	0·128 6
(11)	$SQDy(i)$	(10)/(1)	0·0377 2	0·0347 2	0·0257 2
(12)	$f(i)$	(1) − 1	4	4	4
(13)	$Rf(i)$	1/(12)	0·25	0·25	0·25
(14)	$V(1, i)$	(11)/(12)	0·0094 3	0·008 68	0·006 43
(15)	lg $V(1, i)$	lg of (14)	0·975-3	0·939-3	0·808-3
(16)	$f(i)$.lg $V(1, i)$	(12).(15)	3·900-12	3·756-12	3·232-12
(17)	$My(i)$	(6)/(1)	2·90	3·31	3·83
(18)	$n(i) \cdot Qx(i)$	(1)·(3)	20·563 92	22·344 98	24·376 32
(19)	$n(i) \cdot x(i)$	(1)·(2)	10·14	10·57	11·04
(20)	$x(i) \cdot Sy(i)$	(2)·(6)	29·446 56	34·944 42	42·327 36
(21)	$QSy(i)/n(i)$	(9)/(1)	42·166 08	54·648 18	73·497 78
(22)	$SSQDy$	(11) summed	0·098 16		
(23)	SRf	(13) summed	0·75		
(24)	$f(1)$	(12) summed	12		
(25)	$Rf(1)$	1/(24)	0·083		
(26)	$V(1)$	(22)/(24)	0·008 2		
(27)	lg $V(1)$	lg of (26)	0·914-3		
(28)	$L(1)$	(24)·(27)	10·968-36		
(29)	L	(16) summed	10·888-36		
(30)	$L(1) - L$	(28) − (29)	0·080		
(31)	RF	(23) − (25)	0·67		
(32)	$RF/3(k-1)$	(31)/3(k − 1)	0·11		
(33)	c	1 + (32)	1·11		
(34)	χ^2	2·3(30)/(33)	0·17		
(35)	$\chi^2(0{\cdot}95, k-1)$	from Table of Annex A	6·0		
(36)	N	(1) summed	15		
(37)	Sx	(19) summed	31·75		
(38)	Mx	(37)/(36)	2·116 7		
(39)	SQx	(18) summed	67·285 22		

Table 3 (*Continued*)

(40)	$N \cdot SQx$	(36)·(39)	1 009·278 3			
(41)	QSx	(37) squared	1 008·062 5			
(42)	$N \cdot SQDx$	(40)−(41)	1·215 8			
(43)	$SQDx$	(42)/(36)	0·081 05			
(44)	Sy	(6) summed	50·22			
(45)	My	(44)/(36)	3·348			
(46)	$SPxy$	(20) summed	106·718 34			
(47)	$N \cdot SPxy$	(36)·(46)	1 600·775 1			
(48)	$Sx \cdot Sy$	(37)·(44)	1 594·485 0			
(49)	$N \cdot SPDxy$	(47)−(48)	6·290 1			
(50)	$SPDxy$	(49)/(36)	0·419 34			
(51)	b	(50)/(43)	5·174			
(52)	$b \cdot Mx$	(51)·(38)	10·952			
(53)	a	(45)−(52)	−7·604			
(54)	SQy	(21) summed	170·312 0			
(55)	$N \cdot SQy$	(36)·(54)	2 554·680			
(56)	QSy	(44) squared	2 522·048			
(57)	$N \cdot SQDy$	(55)−(56)	32·632			
(58)	$SQDy$	(57)/(36)	2·175 47			
(59)	$b \cdot SPDxy$	(51)·(50)	2·169 67			
(60)	$SQDMy$	(58)−(59)	0·005 80			
(61)	$f(2)$	$k-2$	1			
(62)	$V(2)$	(60)/(61)	0·005 8			
(63)	F	(62)/(26)	0·7			
(64)	$F(0{\cdot}95, k-2, N-k)$	from Table of Annex A	4·8			
(65)	$SSSQDy$	(22)+(60)	0·103 96			
(66)	f	(36)−2	13			
(67)	V	(65)/(66)	0·008 00			
(68)	$1/N$	1/36	0·0667			
(69)	$t(0{\cdot}95, N-2)$	from Table of Annex A	1·77			
(70)	θ		220	200	180	160
(71)	Θ	(70)+273	493	473	453	433
(72)	X	10^3/(71)	2·028	2·114	2·208	2·309
(73)	$b \cdot X$	(51)·(72)	10·493	10·938	11·424	11·947
(74)	Y	(73)+(53)	2·889	3·334	3·820	4·343
(75)	DX	(72)−(38)	−0·088 7	−0·002 7	0·092 3	0·192 3
(76)	QDX	(75) squared	0·007 87	0·000 01	0·008 34	0·036 98
(77)	$QDX/SQDx$	(76)/(43)	0·097 10	0·000 12	0·102 90	0·456 26
(78)	C	(68)+(77)	0·163 8	0·066 8	0·169 6	0·523 0
(79)	$V(Y)$	(67)·(78)	0·001 31	0·000 53	0·001 36	0·004 18
(80)	$s(Y)$	square root of (79)	0·036	0·023	0·037	0·065
(81)	$t \cdot s(Y)$	(69)·(80)	0·064	0·041	0·065	0·115
(82)	$Y(c)$	(74)−(81)	2·825	3·293	3·755	4·228
(83)	$t(c)$	$\lg^{-1}$ of (82)	668	1 960	5 690	16 900
(84)	t	$\lg^{-1}$ of (74)	774	2 160	6 610	22 000

Table 3 (*Concluded*)

(85)	*T*		5 000	20 000
(86)	*Y*	lg of (85)	3·699	4·301
(87)	*Y*−*a*	(86)−(53)	11·303	11·905
(88)	*X*	(87)/(51)	2·185	2·301
(89)	Θ	10^3/(88)	458	435
(90)	θ	(89)−273	185	162
(91)	*DX*	(88)−(38)	0·068 3	
(92)	*QDX*	(91) squared	0·004 66	
(93)	*QDX*/*SQDx*	(92)/(43)	0·057 6	
(94)	*C*	(68)+(93)	0·124 3	
(95)	*V*(*Y*)	(67)·(94)	0·000 99	
(96)	*s*(*Y*)	square root of (95)	0·032	
(97)	*CV*	(96)/(86)	0 009	
(98)	*Qt*	(69) squared	3·13	
(99)	*V*·*Qt*	(67)·(98)	0·025	
(100)	*V*·*Qt SPDxy*	(99)/(50)	0·060	
(101)	*b*(*r*)	(51)−(100)	5·114	
(102)	*b*(*r*)/*b*	(101)/(51)	0·988	
(103)	*b*(*r*)/*b*·*N*	(102)·(68)	0·065 9	
(104)	*C*(*r*)	(103)+(93)	0·123 5	
(105)	*V*(*r*)	(67)·(104)	0·000 99	
(106)	*s*(*r*)	square root of (105)	0·031 4	
(107)	*t*·*s*(*r*)	(69)·(106)	0·055 6	
(108)	*t*·*s*(*r*)/*b*(*r*)	(107)/(101)	0·010 9	
(109)	*DY*	(86)−(45)	0·351	
(110)	*DY*/*b*(*r*)	(109)/(101)	0·068 6	
(111)	*X*(*c*)	(38)+(110)+(108)	2·196	
(112)	Θ(*e*)	10^3/(111)	455	
(113)	θ(*c*)	(112)−273	182	

A total of at least $N = 30$ specimens are prepared and tested in advance by the proof test. Any failures are replaced. Ten specimens selected at random are then exposed at each of the three temperatures, that is, $k = 3$ ($i = 1, 2, 3$) and $n_i = 10$ ($j = 1, 2, \ldots 10$).

After each exposure at the specified times t_p hours, the specimens are removed from the oven and tested by the proof test. The specimens withstanding the test are restored to the oven for another cycle, while for those failing, the number of cycles, *p*, to which they have been exposed, is noted (Table 4). The time to failure is taken as the midpoint of the last cycle, that is $t = t_p \cdot (p - 0{\cdot}5)$.

The calculation of the variables $y = \lg t$, and x_1, the reciprocal thermodynamic temperature, is shown in Table 4. For convenience the values of *x* have been multiplied by 1 000.

The calculations then proceed as in example 1; see Table 6, where the numbers in parentheses refer to the corresponding items in Table 3.

7.3 Example 3 : Destructive Measurements

A material is tested by destructive measurement of a property, for instance tensile strength according to IS 8504 (Part 2) : 1983 Table 2 (Test 2.1). The end-point criterion is a decrease in strength to below 50% of the initial value.

From earlier experience it is presumed that the logarithm of the tensile strength is a linear function of time.

The expected temperature range corresponding to an extrapolated time failure of 20 000 h is 150°C to 159°C. Three exposure temperatures θ °C and exposure periods t_p hours are selected

Table 4 Test Data

(*Clause* 7.2)

	i	1	2	3
Exposure temperature	θ	200	180	160
Time in hours per cycle	t_p	48	168	672
Item number	j	Number of cycles p		
	1	14	7	7
	2	10	13	7
	3	8	7	6
	4	10	6	7
	5	14	9	9
	6	11	8	7
	7	9	11	9
	8	12	12	11
	9	8	6	8
	10	9	10	8

Table 5 Calculation of the Variables x and y

(*Clause* 7.1)

i	1		2		3	
n	10		10		10	
θ	200		180		160	
$x = \frac{10^3}{\theta + 273}$	2·114		2·208		2·309	
j	t	y	t	y	t	y
1	648	2·81	1 092	3·04	4 368	3·64
2	456	2·66	2 100	3·32	4 368	3·64
3	360	2·56	1 092	3·04	3 696	3·57
4	456	2·66	924	2·97	4 368	3·64
5	648	2·81	1 428	3·15	5 712	3·76
6	504	2·70	1 260	3·10	4 368	3·64
7	408	2·61	1 764	3·25	5 712	3·76
8	552	2·74	1 932	3·29	7 056	3·85
9	360	2·56	924	2·97	5 040	3·70
10	408	2·61	1 596	3·20	5 040	3·70

Table 6 Calculation of *TEP*

(*Clause* 7.2)

	1	2	3	4
(1)	10	10	10	
(2)	2·114	2·208	2·309	
(3)	4·468 995	4·875 264	5·331 48 1	
(4)	2·81	3·04	3·64	
	2·66	3·32	3·64	
	2·56	3·04	3·57	
	2·66	2·97	3·64	
	·81	3·15	3·76	
	2·70	3·10	3·64	
	2·61	3·25	3·76	
	2·74	3·29	3·85	
	2·56	2·97	3·70	
	2·61	3·20	3·70	
(5)	7·896 1	9·241 6	13·249 6	
	7·075 6	11·022 4	13·249 6	
	6·553 6	9·241 6	12·744 9	
	7·075 6	8·820 9	13·249 6	
	7·896 1	9·922 5	14·137 6	
	7·290 0	9·610 0	13·249 6	
	6·812 1	10·562 5	14·137 6	
	7·507 6	10·824 1	14·822 5	
	6·553 6	8·820 9	13·690 0	
	6·812 1	10 240 0	13·690 0	
(6)	26·72	31·33	36·90	
(7)	71·472 4	98·306 5	136·221 0	
(8)	714·724	983·065	1362·210	
(9)	713·958 4	981·568 9	1361·610 0	
(10)	0·765 6	1·496 1	0·600 0	
(11)	0·076 56	0·1496 1	0·060 00	
(12)	9	9	9	
(13)	0·111	0·111	0·111	
(14)	0·008 51	0·016 62	0·006 67	
(15)	0·930-3	0·221-2	0·824-3	
(16)	8·370-27	1·989-18	7·416-27	
(17)	2·672	3·133	3·690	
(18)	44·689 95	48·752 64	53·314 81	
(19)	21·14	22·08	23·09	
(20)	56·486 08	69·176 64	85·202 10	
(21)	71·395 84	98·156 89	136·161 00	
(22)		0·286 17		
(23)		0·333		
(24)		27		
(25)		0·037		
(26)		0·010 6		
(27)		0·025-2		
(28)		0·675-54		
(29)		17·775-72		
(30)		0·900		

Table 6 (*Continued*)

	1	2	3	4
(31)		0·296		
(32)		0·05		
(33)		1·05		
(34)		1·97		
(35)		6·0		
(36)		30		
(37)		66·31		
(38)		2·210 3		
(39)		146·757 4		
(40)		4 402·722 0		
(41)		4 397·016 1		
(42)		5·705 9		
(43)		0·190 20		
(44)		94·95		
(45)		3·165		
(46)		210·864 82		
(47)		6 325·944 6		
(48)		6 296·134 5		
(49)		29·810 1		
(50)		0·993 67		
(51)		5·224		
(52)		11·547		
(53)		—8·382		
(54)	305·713 73			
(55)	9 171·411 9			
(56)	9 015·502 5			
(57)	155·909 4			
(58)	5·196 98			
(59)	5·190 93			
(60)	0·006 05			
(61)	1			
(62)	0·006 05			
(63)	0·6			
(64)	4·2			
(65)	0·292 22			
(66)	28			
(67)	0·010 44			
(68)		0·033 33		
(69)		1·70		
(70)	200	180	160	140
(71)	473	453	433	413
(72)	2·114	2·208	2·309	2·421
(73)	11·044	11·535	12·062	12·647
(74)	2·662	3·153	3·680	4·265
(75)	−0·096 3	−0·002 3	0·098 7	0·210 7
(76)	0·009 27	0·000 01	0·009 74	0·044 39

Table 6 (*Concluded*)

	1	2	3	4
(77)	0·048 74	0·000 05	0·051 21	0·233 39
(78)	0·082 1	0·033 4	0·084 5	0·266 7
(79)	0·000 86	0·000 35	0·000 88	0·002 78
(80)	0·029	0·019	0·030	0·053
(81)	0·049	0·032	0·051	0·090
(82)	2·613	3·121	3·629	4·175
(83)	410	1 320	4 260	15 000
(84)	459	1 420	4 790	18 400
(85)	5 000	20 000		
(86)	3·699	4·301		
(87)	12·081	12·683		
(88)	2·313	2·428		
(89)	432	412		
(90)	159	139		
(91)	0·102 7			
(92)	0·010 55			
(93)	0·055 5			
(94)	0·088 8			
(95)	0·000 93			
(96)	0·030			
(97)	0·008			
(98)	2·89			
(99)	0·030			
(100)	0·030			
(101)	5·194			
(102)	0·994			
(103)	0·033 1			
(104)	0·088 6			
(105)	0·000 92			
(106)	0·030 3			
(107)	0·051 5			
(108)	0·009 9			
(109)	0·534			
(110)	0·102 8			
(111)	2·323			
(112)	430			
(113)	157			

from Table 1, namely, 48 h at 210°C, 168 h at 190°C, and 672 h at 170°C.

About 200 specimens are prepared. Ten of these are selected at random and aged for 48 h at 170°C, and then measured for determination of the initial value of the tensile strength. By random selection the remaining specimens are divided into three groups, which are exposed in three ovens, the measured oven temperatures being 212°C, 190°C and 171°C. At the end of each period, five specimens are measured for tensile strength and then discarded. The strength is expressed as lg p, the logarithm of the measured value divided by the initial value. The end-point criterion then becomes $\lg p_e = \lg 0{\cdot}5 = 0{\cdot}699\,0 - 1$.

The values of lg p thus obtained are given in Table 7 at the four measuring times closest to the point where the median of the five measured values crosses the end-point line as shown in Fig. 2, in the case of $\theta = 212$°C.

At each of the three exposure temperatures a line which makes a best fit to measured points is determined by the method of least squares as follows:

The coefficients in the equation

$$y = a + bx.$$

where y stands for lg p and x for time of measurement t_m, are calculated as

$$b = \frac{\Sigma\,(x_i - \bar{x})\bar{y}_i}{\Sigma\,(x_i - \bar{x})^2}$$

$$a = \frac{\Sigma\,\bar{y}_i}{k} - b\bar{x}$$

where

$$\bar{x} = \frac{\Sigma\,x_i}{k}$$

$$\bar{y}_i = \frac{\Sigma\,y_{ij}}{n_i}$$

k = 4, number of times used in the calculation at each temperature, (i = 1, 2, 3, 4) and

n_i = 5, number of specimens tested at each time (j = 1, 2,...5).

The calculations are shown in Table 8.

For each specimen a line is drawn parallel to the best fitting line as shown in Fig. 2 in the case of $\theta = 212$°C. The time where that line crosses the end-point line is taken as the individual time to failure of the specimen. The time to failure may also be calculated as

$$t = t_m + \frac{\lg p_e - \lg p}{b}$$

where t_m is the time of measurement, and $\lg p_e = 0{\cdot}699\,0 - 1$ is the end-point criterion.

This means that if it is supposed that the specimen had been tested at time t instead of at time t_m the measured value would have been p_e instead of the actually measured value p.

The supposed times to failure t_{ij} thus obtained are given in Table 9.

The calculation of the thermal endurance profile then proceeds as in example 1 (**6.1**)

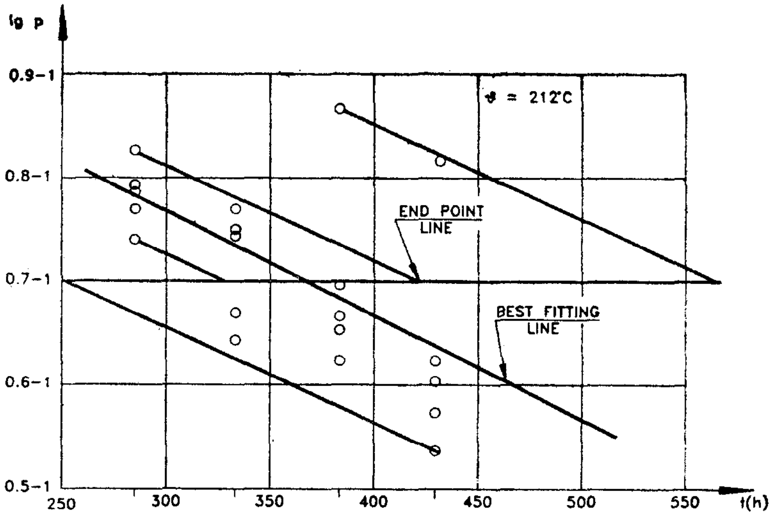

FIG. 2 DETERMINATION OF THE SUPPOSED TIME TO FAILURE (DESTRUCTIVE ELEMENTS)

with three temperatures ($k = 3$) and twenty specimens at each temperature ($n_i = 4 \cdot 5 = 20$), or with a total of $N = kn_i = 60$ specimens.

Table 10 shows the calculations when made on an electronic desk calculator with built-in statistical programmes for determination of mean value, standard deviation, and linear regression coefficients.

The thermal endurance profile is determined to be

TEP = 156/174 (173).

Table 7 Test Data

(*Clause* 7.3)

θ					
212		190		171	
*t*m	lg *p*	*t*m	lg *p*	*t*m	lg *p*
288	0·834 - 1	1 344	0·754 - 1	5 376	0·711 - 1
	0·789 - 1		0·784 - 1		0·667 - 1
	0·781 - 1		0·709 - 1		0·814 - 1
	0·766 - 1		0·835 - 1		0·841 - 1
	0·743 - 1		0·709 - 1		0·726 - 1
336	0·752 - 1	1 512	0·750 - 1	6 048	0·748 - 1
	0·664 - 1		0·602 - 1		0·709 - 1
	0·735 - 1		0·750 - 1		0·821 - 1
	0·640 - 1		0·772 - 1		0·712 - 1
	0·737 - 1		0·668 - 1		0·641 - 1
384	0·635 - 1	1 680	0·602 - 1	6 720	0·649 - 1
	0·871 - 1		0·718 - 1		0·637 - 1
	0·661 - 1		0·599 - 1		0·633 - 1
	0·669 - 1		0·613 - 1		0·713 - 1
	0·696 - 1		0·599 - 1		0·667 - 1
432	0·619 - 1	1 848	0·656 - 1	7 392	0·529 - 1
	0·550 - 1		0·544 . 1		0·512 - 1
	0·819 - 1		0·506 - 1		0.749 - 1
	0·519 - 1		0·601 - 1		0·593 - 1
	0·601 - 1		0·662 - 1		0·760 - 1

Table 8
(*Clause* 7.3)

θ	212	190	171
y_1, i = 1	0·782 6 - 1	0·758 2 - 1	0·751 8 - 1
2	0·705 6 - 1	0·708 4 - 1	0·726 2 - 1
3	0·706 4 - 1	0·626 2 - 1	0·659 8 . 1
4	0·621 6 - 1	0·593 8 - 1	0·628 6 - 1
$\bar{x}$	360	1 596	6 384
b	−0·001 005	−0·000 342 5	−0·000 064 88
a	0·065 7	0·218 3	0·1 05 8

Table 9 Supposed Times to Failure t_{ij}
(*Clause* 7.3)

θ		
212	190	171
422	1 505	5 561
378	1 592	4 883
370	1 373	7 149
355	1 741	7 565
332	1 373	5 793
389	1 661	6 804
301	1 229	6 203
372	1 661	7 929
277	1 725	6 249
374	1 422	5 155
320	1 397	5 950
555	1 736	5 765
346	1 388	5 703
354	1 429	6 936
381	1 388	6 227
352	1 723	4 772
284	1 396	4 510
551	1 285	8 163
253	1 562	5 759
334	1 740	8 333

Table 10

(*Clause* 7.3)

$N = 60,\ k = 3,\ n_i = 20$

$$f_i = n_i - 1 = 19,\ f_1 = k f_i = 57,\ f = N - 2 = 58,\ c = 1 + \frac{\left(\frac{k}{f_i} - \frac{1}{f_1}\right)}{3(k-1)} = 1{\cdot}023\ 4$$

θ	212	190	171	
i	1	2	3	
$x_i = \frac{1}{\theta + 273}$	0·002 062	0·002 160	0·002 252	
$\Sigma y_{ij} = \Sigma \lg t_{ij}$	51·083 1	63·564 5	75·815 1	
Σy^2_{ij}	130·609 655	202·066 656	287·509 901	
$\bar{y}_i = \frac{\Sigma y_{ij}}{n_i}$	2·554 2	3·178 2	3·790 6	
$s_{1i}^2 = \frac{n_i \Sigma y^2_{ij} - (\Sigma y_{ij})^2}{n_i f_i}$	0·007 129 0	0·002 348 6	0·005 968 5	
$s_1^2 = \frac{\Sigma s_{1i}^2}{k}$		0·005 148 7		
$\chi^2 = \frac{f_1 \ln s_1^2 - \Sigma f_i \ln s_{1i}^2}{c}$		5·8		
$\chi^2 (0{\cdot}95, k - 1)$		6·0		
$\bar{x} = \frac{\Sigma x_i}{k}$		0·002 158		
$b = \frac{\Sigma (x_i - \bar{x}) \bar{y}_i}{\Sigma (x_i - \bar{x})^2}$		6 494		
$a = \frac{\Sigma \bar{y}_i}{k} - b\bar{x}$		−10·839		
$Y_i = a + b x_i$	2·550 2	3·186 4	3·786 6	
$s_2^2 = \frac{\Sigma n_i (\bar{y} - Y_i)^2}{(k-2)}$		0·001 998 4		
$F = \frac{s_2^2}{s_1^2}$		0·4		
$F (0{\cdot}95, k\ \ 2, f_1)$		4·0		
$s^2 = \frac{f_1 s_1^2 + (k - 2) s_2^2}{f}$		0·005 094 4		
s		0·071 4		
$t (0{\cdot}95, f)$		1·68		
θ	210	190	170	150
X	0·002 070	0·002 160	0·002 257	0·002 364
$Y = a + bX$	2·606	3·186	3·820	4·513
$\Sigma n_i (x_i - \bar{x})^2$		3·652 $6 10^{-7}$		

Table 10 (*Concluded*)

$s_y^2 = s^2 \left[\frac{1}{N} + \frac{(X - \bar{x})^2}{\Sigma n_i (x_i - \bar{x})^2} \right]$	0·000 195	0·000 086	0·000 226	0·000 689
$Y_c = Y - ts_y$	2·582	3·171	3·794	4·468
$t_c = \lg^{-1} Y$	403	1 540	6 600	32 600
$t_c = \lg^{-1} Y_c$	382	1 480	6 230	29 400
T	5 000		20 000	
$\theta = \frac{b}{\lg T - a} - 273$	174		156	
$X_i = \frac{1}{\theta + 273}$	0·002 239		0·002 331	
$s_y^2 = s^2 \left[\frac{1}{N} + \frac{(X_1 - \bar{x})^2}{\Sigma n_i (x_i - \bar{x})^2} \right]$	0·000 178			
$CV = \frac{s\bar{y}}{\lg T}$	0·004			
$b_r = b - \frac{t^2 s^2}{b \, \Sigma n_i (x_i - \bar{x})^2}$	6 487			
$s_r^2 = s^2 \left[\frac{b_r}{Nb} + \frac{(X_1 - \bar{x})^2}{\Sigma n_1 (x_1 - \bar{x})^2} \right]$	0·000 178		0·000 513	
$X_c = \bar{x} + \frac{\lg T - \bar{y}}{b_r} + \frac{ts_r}{b_r}$	0·002 242		0·002 338	
$\theta_c = \frac{1}{X_c} - 273$	173		155	

ANNEX A

(*Clauses* 3, 6.1, 6.3 *and* 6.4)

0·95 FRACTILES OF THE χ^2, t AND F DISTRIBUTIONS

This table gives the values of χ^2 (0·95, f), t (0·95, f) and F (0·95, f_n, f_d), where f_n is the number of degrees of freedom of the numerator, and f_d of the denominator in the expression

$$F = \frac{s^2_n}{s^2_d}$$

f	χ^2	t
1	3·8	6·31
2	6·0	2·92
3	7·8	2·35
4	9·5	2·13
5	11·1	2·02
6	12·6	1·94
7	14·1	1·90
8	15·5	1·86
9	16·9	1·83
10	18·3	1·81
11	19·7	1·80
12	21·0	1·78
13	22·4	1·77
14	23·7	1·76
15	25·0	1·75
16	26·3	1·75
17	27·6	1·74
18	28·9	1·73
19	30·1	1·73
20	31·4	1·73
25	37·7	1·71
30	43·8	1·70
40	55·8	1·68
50	67·5	1·68
100	124·3	1·66
500	553·2	1·65

f_n / f_d	F				
	1	2	3	4	5
1	161	200	216	225	230
2	19	19	19	19	19
3	10·1	9·6	9·3	9·1	9·0
4	7·7	6·9	6·6	6·4	6·3
5	6·6	5·8	5·4	5·2	5·1
6	6·0	5·1	4·8	4·5	4·4
7	5·6	4·7	4·4	4·1	4·0
8	5·3	4·5	4·1	3·8	3·7
9	5·1	4·3	3·9	3.6	3·5
10	5·0	4·1	3·7	3·5	3·3
11	4·8	4·0	3·6	3·4	3·2
12	4·8	3·9	3·5	3·3	3·1
13	4·7	3·8	3·4	3·2	3·0
14	4·6	3·7	3·3	3·1	3·0
15	4·5	3·7	3·3	3·1	2·9
16	4·5	3·6	3·2	3·0	2·9
17	4·5	3·6	3·2	3·0	2·8
18	4·4	3·6	3·2	2·9	2·8
19	4·4	3·5	3·1	2·9	2·7
20	4·4	3·5	3·1	2·9	2·7
25	4·2	3·4	3·0	2·8	2·6
30	4·2	3·3	2·9	2·7	2·5
40	4·1	3·2	2·8	2·6	2·5
50	4·0	3·2	2·8	2·6	2·4
100	3·9	3·1	2·7	2·5	2·3
500	3·9	3·0	2·6	2·4	2·2

ANNEX B

LIST OF SYMBOLS

Symbol		*Clause or Sub-clause*
a	Regression coefficient	6.2, 7.3
b	Regression coefficient	6.2, 7.3
b_r	Intermediate constant	6.7
c	Intermediate constant	6.1
CV	Coefficient of variation	6.5
f	Number of degrees of freedom of s^2	6.3
f_i	Number of degrees of freedom of s_{1i}^2	6.1
f_1	Number of degrees of freedom of s_1^2	6.1
f_2	Number of degrees of freedom of s_2^2	6.3
F	Fisher-distributed stochastic variable	6.3
i	Order number of exposure temperature	6
i	Order number of time of measurement	7.3
j	Order number of specimen within sample	6
k	Number of exposure temperatures	6
k	Number of times of measurement	7.3
n_i	Number of specimens exposed at θ_i	6
n_i	Number of specimens tested at each time	7.3
N	Total number of specimens	6
p	Number of cycles	7.2
p	Arbitrary property	7.3
p_e	Endpoint	7.3
s^2	Pooled variance	6.3
s_y^2	Variance of Y	6.4
s_1^2	Weighted mean of s_{1i}^2	6.1
s_2^2	Variance about regression line	6.3
s_{1i}^2	Variance within set of specimens exposed at θ_i	6.1
t	Student-distributed stochastic variable	6.4
t	Time to failure/hours	7.2
t_{ij}	Time to failure/hours of specimen No. j exposed at θ_i	6
t_p	Time per cycle/hours	7.2
t_m	Time of measurement/hours	7.3
x	Independent variable	6.2, 7.3
x_i	Value of x corresponding to θ_i	6
x_i	Time of measurement/hours	7.3
$\bar{x}$	Weighted mean of x_i	6.2, 7.3
X	Value of x at specified value of y from regression equation	6.4, 7.3
X_c	Upper unilateral 95% confidence limit on x	6.7
X_5	Value of x corresponding to Y_5	6.5
X_{20}	Value of x corresponding to Y_{20}	6.6
y	Dependent variable, lg t	6.2
y	Dependent variable, lg p	7.3
y_{ij}	Value of y for specimen No. j exposed at θ_i	6

Symbol		*Clause or Sub-clause*
y_{ij}	Value of y for specimen No. j at time x_i	7.3
$\bar{y}$	Total mean of y_{ij}	6.2
$\bar{y}_i$	Sample mean at x_i	6.2, 7.3
Y	Value of y at specified value of x from regression equation	6.4
Y_c	Lower unilateral 95% confidence limit on y	6.4
Y_5	Value of y corresponding to 5 kh to failure	6.5
θ_c	Lower unilateral 95% confidence limit on θ_5	6.7
θ_i	Exposure temperature in degrees Celsius	6
θ_5	Estimated temperature in degrees Celsius giving 5 kh to failure	6.6
θ_{20}	Estimated temperature in degrees Celsius giving 20 kh to failure	6.6
χ^2	Chi-square-distributed stochastic variable	6.1

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This Indian Standard has been developed from Doc : No. ETD 02 (3701).

Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

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Printed at New India Printing Press, Khurja, India